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Sh.S.EREMYAN, A.E. NAZARYAN

PRODUCTION AND DECAYS INVOLVING PSEUDOSCALAR GLUEBALLS

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PRODUCTION AND DECAYS INVOLVING PSEUDOSCALAR GLUEBALLS

The production and decay reactions containing η, η' and ι(1440) mesons are considered to clarify the quark composi - tion of those mesons, as well as to obtain information on quark - gluon mixing in them. We have given the predictions for large number of the two-body decays with the η, η' and ι(1440) pseudoscalr glueballs, and also the ones for the differentia cross sections of production of those glueballs in the hyper-charge exchange reactions.

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Yerevan 1985

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Ш.С.ЕРЕМЯН, А.Э.НАЗАРЯН

ПРОЦЕССЫ С РОЖДЕНИЯМИ И РАСПАДАМИ, СОДЕРЖАЩИЕ ПСЕВДОСКАЛЯРНЫЕ ГЛЮОНИИ

Рассмотрены реакции рождения и распады, содержащие η, η' и $\iota(1440)$ мезоны для выяснения кваркового состава этих мезонов, а также получения информации о кварк-глюонном смешивании в них. Приводятся предсказания для большого числа двухчастичных распадов с участием η, η' и $\iota(1440)$ псевдоскалярных глюониев, а также предсказания дифференциальных сечений рождения этих глюониев в реакциях с обменом гиперзаряда.

Ереванский физический институт
Ереван 1985

1. Introduction

As is known, the gauge theory of the strong interactions, quantum chromodynamics (QCD), involves quanta (gluons) which are expected to form bound states with each other. In general, these gluonic bound states can be expected to mix with neutral isoscalar mesons composed of quark-antiquark pairs. In particular, both recent candidates for gluonic bound states $\iota(1440)$: $J^{PC}=0^{-+}$ /1/, $\Theta(1690)$; $J^{PC}=2^{++}$ /2/ may have quark-antiquark admixtures. This can be checked up in different ways. For example, Rosner /3/ has introduced a simple test of quark admixtures in neutral mesons based on radiative decays.

Kawai /4/ has paid attention to the fact that not only $\iota\gamma$ but also $\eta\gamma$ and $\eta'\gamma$ were detected in radiative J/ψ decay products. All these processes can proceed via two or more gluons annihilated by the ortho-charmonium, as this fact exemplifies that there are gluon admixtures in η, η' mesons. Furthermore, there is a set of experimental data on πN and KN reactions involving η and η' productions. As for the correct description of the available experimental data on processes involving η , η' and ι mesons, the mixing of these mesons should be assumed.

In this paper we assume that the mixing should occur between η , η' , and ι , and use the Regge description of $\bar{\pi} p \to \eta(\eta') n$, $\eta(\eta') \to \gamma\gamma$ reactions to determine the mixing parameters. In Sec.2 we have described the model takes into account the η , η' and ι mixing by means of the quadratic mass matrix. Sec.3 presents the Regge description of the $\bar{\pi} p \to \eta(\eta') n$, $\eta(\eta') \to \gamma\gamma$ reactions. In sec.4 we have defined the values of the model parameter. In Sec.5 we have given the predictions of the model for the large number of the two-body decays with the η , η' and ι pseudoscalar glueballs, as well as those for the differential cross sections of production of those glueballs in the hypercharge exchange reactions.

2. The Mixing Matrix for Pseudoscalar Mesons

We shall be working on the basis containing the following states:

$$|N\rangle \equiv \frac{1}{\sqrt{2}} |\bar{u}u + \bar{d}d\rangle , \tag{1}$$

$$|S\rangle \equiv |\bar{s}s\rangle , \tag{2}$$

$$|G\rangle \equiv |gluonium\rangle . \tag{3}$$

A physical state ψ is their linear combination

$$|\psi\rangle = x|N\rangle + y|S\rangle + z|G\rangle \tag{4}$$

where

$$x^2 + y^2 + z^2 = 1 . \tag{5}$$

The gluonic admixture in the physical state is possible if only $z^2 = 1 - x^2 - y^2 > 0$. We shall neglect everywhere the small $\bar{c}c$ admixture in the states under consideration and neglect also mixing with radial excitations, although they may be essential at more exact consideration of ι (1440).

There exists a considerable difference between the effective masses of strange and nonstarange quarks, which becomes particularly noticeable in the pseudoscalar meson case. This difference was considered the main cause of all effects of the SU(3) symmetry breaking, including the octet-singlet mixing. However the introduction of gluons violates essentially this picture, since they can destruct and reform both the strange and normal quarkonia. Moreover, they can mix gluonium with quarkonium. Hence the general case, the meson-gluon mixing becomes inevitable.

The ideal basis $\{|N\rangle, |S\rangle, |G\rangle\}$ contains the state vectors of normal and strange quarkonia and pure gluonia. It is evident enough /3-5/, that $|N\rangle$ is the orthogonal partner of $|\pi^0\rangle$, and one may assume that $m_N^2 = m_{\pi^0}^2$. As for the Gell-Mann-Okubo mass formula yields $m_S^2 = 2m_K^2 - m_\pi^2$ The gluons, due to confinement, acquire some effective mass m_G so one may show /4/ that $m_G^2 \simeq 2 \langle k_T^2 \rangle$ for the two-gluonic gluonium, where $\langle k_T^2 \rangle$ are fluctuations over transverse momentum of the constituent gluons.

As was mentioned by many authors (see, e.g. /3-5/), the annihilation of the $\bar{q}q$-system into gluons is responsible for the strong mixing of the pseudoscalar states in QCD. Hence, the corresponding terms must be added to the mass matrix of isoscalar mesons. In the lowest order of the perturbation theory the annihilation terms for the pseudoscalar mesons consist of two gluons.

Then, the quadratic mass matrix for the pseudoscalar mesons including the annihilation terms λ_i can be written as follows /4/:

$$\hat{M} = \begin{pmatrix} m_N^2 + 2\lambda_N^2 & \sqrt{2}\lambda_N\lambda_s & \sqrt{2}\lambda_N\lambda_G \\ \sqrt{2}\lambda_N\lambda_s & m_s^2 + \lambda_s^2 & \lambda_s\lambda_G \\ \sqrt{2}\lambda_N\lambda_G & \lambda_s\lambda_G & m_G^2 + \lambda_G^2 \end{pmatrix} \qquad (6)$$

Here λ_i means the contribution of the annihilation term into the matrix element describing transitions $\bar{q}_i q_i \rightleftarrows \bar{q}_j q_j$. As distinct from Ref.3, we choose a quadratic mass matrix, since the mass formulae for the meson mass square are fulfilled much more better /6/.

In this matrix we have four unknown parameters $m_G, \lambda_N, \lambda_s$ and λ_G. Hence we need at least four equations to define those parameters.

The physical eigenstates $|\Psi\rangle$ must satisfy the equation for the eigenvalues

$$\hat{M}|\Psi\rangle = M|\Psi\rangle \qquad (7)$$

where

$$|\Psi\rangle = \begin{pmatrix} |\eta\rangle \\ |\eta'\rangle \\ |i\rangle \end{pmatrix}, \quad M = \begin{pmatrix} m_\eta^2 & & 0 \\ & m_{\eta'}^2 & \\ 0 & & m_i^2 \end{pmatrix} \qquad (8)$$

From the condition of equality to zero of the system (7) determinant we obtain three equations

$$\begin{aligned} & m_N^2 m_s^2 m_G^2 + 2\lambda_N^2 m_s^2 m_G^2 + \lambda_s^2 m_N^2 m_G^2 + \lambda_G^2 m_N^2 m_s^2 = m_\eta^2 m_{\eta'}^2 m_i^2 \\ & m_N^2 m_s^2 + (m_N^2 + m_s^2) m_G^2 + 2\lambda_N^2 m_s^2 + \lambda_s^2 m_N^2 + \lambda_G^2 (m_N^2 + m_s^2) + \\ & \quad + (2\lambda_N^2 + \lambda_s^2) m_G^2 = m_\eta^2 m_{\eta'}^2 + m_{\eta'}^2 m_i^2 + m_\eta^2 m_i^2, \qquad (9) \\ & m_N^2 + m_s^2 + m_G^2 + 2\lambda_N^2 + \lambda_s^2 + \lambda_G^2 = m_\eta^2 + m_{\eta'}^2 + m_i^2 . \end{aligned}$$

Further, we shall define the unitary matrix U which transforms the ideal basis into the physical one $\{|N\rangle, |S\rangle, |G\rangle\} \to \{|\eta\rangle, |\eta'\rangle, |i\rangle\}$ then $U \hat{M} U^{-1}$ is to be a diagonal matrix with diagonal elements m_η^2, $m_{\eta'}^2$ and m_i^2. This condition leads to the following expression for U:

$$U = \begin{pmatrix} x_\eta & y_\eta & z_\eta \\ x_{\eta'} & y_{\eta'} & z_{\eta'} \\ x_i & y_i & z_i \end{pmatrix}, \quad \begin{aligned} |\eta\rangle &= x_\eta|N\rangle + y_\eta|S\rangle + z_\eta|G\rangle, \\ |\eta'\rangle &= x_{\eta'}|N\rangle + y_{\eta'}|S\rangle + z_{\eta'}|G\rangle, \\ |i\rangle &= x_i|N\rangle + y_i|S\rangle + z_i|G\rangle. \end{aligned} \qquad (10)$$

where

$$x_K = \sqrt{2}\lambda_N\lambda_G(m_s^2 - m_K^2) C_K ,$$

$$y_K = \lambda_s\lambda_G(m_N^2 - m_K^2) C_K ,$$

$$Z_K = \left[2\lambda_N^2 \lambda_s^2 - (m_N^2 + 2\lambda_N^2 - m_K^2)(m_s^2 + \lambda_s^2 - m_K^2) \right] C_K ,$$

$$C_K = \Big\{ 2\lambda_N^2 \lambda_G^2 (m_s^2 - m_K^2)^2 + \lambda_s^2 \lambda_G^2 (m_N^2 - m_K^2)^2 + \left[2\lambda_N^2 \lambda_s^2 - (m_N^2 + 2\lambda_N^2 - m_K^2)(m_s^2 + \lambda_s^2 - m_K^2) \right]^2 \Big\}^{-1/2} \quad (11)$$

$$(K = \eta, \eta', i)$$

In order to define the unknown parameters of theory m_G, λ_N, λ_s and λ_G, we already have three equations (9), so we are to choose from the existing experimental data some fourth equation which will just help us to solve the whole system.

3. The Production of Pseudoscalar Glueballs in High Energy Interactions

In Refs./3/ and /4/ the widths of the radiative decays figured as additional equations to define the theory parameters m_G, λ_N, λ_s and λ_G. Unfortunatelly, these widths were defined insufficiently experimentally, which resulted in large errors when defining the model parameters.

The strong interaction processes at high energies were defined with a much better accuracy. Therefore we shall use as a fourth equation the ratio of the cross sections

$$R = \frac{d\sigma/dt(\pi^- p \to \eta' n)}{d\sigma/dt(\pi^- p \to \eta n)} . \quad (12)$$

The cross sections of these processes were measured in 1979 and given in Refs. /7/ and /8/.

Only one Regge trajectory A_2 together with its pomeron branches contributes to the amplitude of processes $\pi^- p \to \eta(\eta')n$. The amplitudes of the process $\pi^- p \to \eta(\eta')n$ with exchange of the A_2 trajectory were parametrized as follows /9/:

$$M_0^{A_2} = \varepsilon_{A_2} \eta_{A_2} a_0^{A_2} e^{\lambda_{0A_2} t} ,$$
$$M_1^{A_2} = \sqrt{-t}\, \varepsilon_{A_2} \eta_{A_2} a_1^{A_2} e^{\lambda_{1A_2} t} , \quad (13)$$

where

$$\varepsilon_{A_2} = \frac{1}{2p\sqrt{s}} \left(\frac{s-u}{2s_0} \right)^{\alpha_{A_2}(0)} ; \quad \eta_{A_2} = i - ctg \frac{\pi}{2} \alpha_{A_2}(0) ;$$
$$\lambda_{iA_2} = R_{iA_2}^2 + \alpha'_{A_2} \left[\ln\left(\frac{s-u}{2s_0} \right) - \frac{i\pi}{2} \right] . \quad (14)$$

The contribution of the branches was calculated using the quasi-eikonal formulae (see, e.g. /9/).

The from of trajectory A_2 was defined in /9/:

$$\alpha_{A_2}(t) = 0.41 + 0.63t .$$

The shower amplification coefficients $C_{0A_2} = C_{1A_2} = 1$. Only four parameters a_0, a_1, R_0^2 and R_1^2, which were defined from the comparison with experimental data of Refs. /7,8/, remain in the model. The obtained values of these parameters for both reactions $\pi^- p \to \eta(\eta')n$ are given in Table 1.

The obtained results for the differential cross sections of the processes $\pi^- p \to \eta(\eta')n$, $\eta(\eta') \to \gamma\gamma$ are given in Figs.1 and 2. The plots of the differential cross sections $\pi^- p \to i\, n$ are not given here, since their dependence on differs weakly from t - behaviour of the cross sections of reactions $\pi^- p \to \eta(\eta')n$.

The earlier results /10/ of the FNAL group are also plotted in Fig.1. In all these experiments they measured only the production cross section $\eta(\eta')$ at the decay $\eta(\eta') \to 2\gamma$ i.e.

$$\pi^- p \to \underset{\hookrightarrow \gamma\gamma}{\eta(\eta')}\, n \equiv \pi^- p \to \eta(\gamma\gamma)[\eta'(\gamma\gamma)]\, n .$$

Hence, in order to calculate correctly the quantity R one should take into account all modes of the decay η and η'. Then we shall have

$$R = \frac{d\sigma/dt(\pi^- p \to \eta'(\gamma\gamma)n)}{d\sigma/dt(\pi^- p \to \eta(\gamma\gamma)n)} \cdot \frac{BR(\eta \to \gamma\gamma)}{BR(\eta' \to \gamma\gamma)} . \tag{15}$$

But actually, a much more important physical information contains the following quantity

$$R_1 = \frac{a_0^{\eta'}}{a_0^{\eta}} \left(\frac{BR(\eta \to \gamma\gamma)}{BR(\eta' \to \gamma\gamma)} \right)^{1/2} \tag{16}$$

which is free from uncertainties contributed by the branches in the cross sections η and η', which generally may be different. R_1 is simply the ratio of the Regge residues $A_2\pi\eta$ and $A_2\pi\eta'$. In our notations (10) we have

$$R_1 = \left| \frac{X_{\eta'}}{X_\eta} \right| = 0.786 \pm 0.068 \tag{17}$$

The partial decay modes were taken from /11/

$$BR(\eta' \to \gamma\gamma) = 0.019 \pm 0.002$$
$$BR(\eta \to \gamma\gamma) = 0.391 \pm 0.008$$

In Ref./8/ it was obtained that

$$R = 0.55 \pm 0.06 \tag{18}$$

If the contributions of the branches into the both processes are the same, then the relation $R_1^2 = R$ must take place.

In our case

$$R_1^2 = 0.618 \pm 0.11$$

which coincides sufficiently exactly with (18) and points out that the contributions of the branches in these reactions almost coincide.

Fig.3 presents the ratio of the cross sections η and η' as a function of transferred momentum. The observed dependence on t is due to the fact that $R^2_{A_2}$ in the both reactions differ somewhat from each other.

Fig.4 shows the polarizations of the reactions $\pi^- p \to \eta(\eta')n$, $\eta(\eta') \to \gamma\gamma$. As is deen from Fig.4, the dependence of the polarization on transferred momentum charges weakly as energy increases.

Thus we have obtained the fourth equation we need to define the four unknown parameters $m_G, \lambda_N, \lambda_S, \lambda_G$.

4. The Definition of the Model Parameters

We have now several possible ways to define the model parameters $m_G, \lambda_N, \lambda_s$ and λ_G :

i) they can be defined by adding to the three equations (9) the fourth one (17)

$$R_1 = \frac{m_s^2 - m_{\eta'}^2}{m_s^2 - m_\eta^2} \frac{C_{\eta'}}{C_\eta} = -0.786 \pm 0.068 \quad (19)$$

ii) one can add to (9) two equations with 2γ decays η and η' as it was done in Ref./4/, and add also

$$\frac{\Gamma(\kappa \to 2\gamma)}{\Gamma(\pi^0 \to 2\gamma)} = \frac{1}{9}\left(\frac{m_\kappa}{m_{\pi^0}}\right)^3 \left[5x_\kappa + \xi\sqrt{2}\, y_\kappa\right]^2, \quad \kappa = \eta, \eta' \quad (20)$$

iii) or use, as in Ref./3/, the whole set of experimental data on radiative decays with participation of the η and η' mesons.

We have tried all the three versions and added also the fourth one which is a combination of the first and the third versions.

The obtained results are given in Table 2.

The comparison of the results of all the four versions shows that the parameters m_G , λ_N , λ_s and λ_G calculated in the four different ways do not practically differ from each other. The difference appears only, in the magnitude of errors of the calculated parameters. The errors are minimal in the fourth version, which is quite natural, since in this case there are nine equations to define the four parameters. The fact that in all the four versions the values of the parameters are practically the same points out, first, that our obtained solution is stable, and second, that the used set

of experimental data is self-consistent.

The same table lists the values of χ^2/n , where n is the number of equations participating in the fitting procedure.

Besides, the table presents the values for x_κ, y_κ and z_κ calculated by formulae (9). These values just define a relative contribution of different states to η , η' and ι (1440) mesons.

It turned out that the η meson contains almost equally from the contributions of $|N\rangle$ and $|S\rangle$ states with a very small admixture of $|G\rangle$. All the three states contribute almost equally to the η' meson. The main contribution to the ι (1440) meson is $|G\rangle$ state, but there is a sufficiently considerable admixture of $|N\rangle$ and $|S\rangle$ states.

5. Some Predictions

The values of x_κ , y_κ and z_κ given in Table 2 can be measured directly in the experiment. Besides, as it was shown in Refs. /3,4/, all the experimentally measurable quantities must be expressed via these mixing parameters. For example, one can give predictions for the radiative decays of η , η' ι (1440) mesons.

In Table 3 are given the predictions for the large number of the two-body decays in which the η , η' and ι (1440) mesons participate. One can see from the Table that the predictions of different versions agree well to each other and differ only by the magnitude of the theoretical error due to the uncertainties of the model parameters. One can say that our parametrization ensures quite a self-consistent pattern of mixing for the pseudoscalr glueballs.

The $i \to \gamma\gamma$ decay may occur only if i has an admixture of $|N\rangle$ and $|S\rangle$ states, i.e. this decay may serve as a test pointing out that i (1440) is not a pure gluonic state. The model predicts that

$$\Gamma(i \to \gamma\gamma) = 5.58 \pm 1.8 \text{ keV}. \tag{21}$$

In Ref. /4/ attention was called to the fact that η, η' and i mesons were found out in the radiative decays of J/ψ. All these decays may occur only via two-gluon annihilation of orthocharmonium. It turned out that the ratio of the widths of the $J/\psi \to \eta\gamma$, $J/\psi \to \eta'\gamma$ and $J/\psi \to i\gamma$ decays is of the same order of magnitude /11/:

$$\begin{gathered} BR(J/\psi \to \eta\gamma) : BR(J/\psi \to \eta'\gamma) : BR(J/\psi \to i\gamma) = \\ = 1.0 : (4.2 \pm 1) : (4.88 \pm 2.4). \end{gathered} \tag{22}$$

This means that their couplings to gluons are the magnitudes of the same order, hence there exists strong mixing of η, η' and i.

The width $\Gamma(J/\psi \to k\gamma)$, $(k = \eta, \eta', i)$ is connected with $\sqrt{2}\lambda_N x_k + \lambda_S y_k + \lambda_G z_k$ /4/. Taking into account the P-wave factor $(1 - m_k^2/m_{J/\psi}^2)^3$ we shall arrive at the following relations

$$\begin{gathered} BR(J/\psi \to \eta\gamma) : BR(J/\psi \to \eta'\gamma) : BR(J/\psi \to i\gamma) = \\ = 1 : (5.42 \pm 0.32) : (6.73 \pm 1.7), \end{gathered} \tag{23}$$

which quite agree with the experimental values of (22).

Recently, there have appeared new data on the width of the decay $J/\psi \to \eta'\gamma$ /12/

$$BR(J/\psi \to \eta'\gamma) = 0.46 \pm 0.04 \pm 0.065$$

which yields

$$BR(J/\psi \to \eta\gamma) : BR(J/\psi \to \eta'\gamma) = 1 : (5.35 \pm 1.) \tag{24}$$

agreeing very well with (23)

Table 3 presents also the ratio

$$R_i = \frac{d\sigma/dt(\pi^- p \to i n)}{d\sigma/dt(\pi^- p \to \eta n)} = 0.28 \pm 0.15. \tag{25}$$

Thus the cross section of the process $\pi^- p \to i n$ turns out not a small quantity and may successfully be measured experimentally. However some complications with the detection of i occur here, since one will have to observe the three-body decays $i \to \bar{K}K\pi$ instead of the simple one $i \to \gamma\gamma$. Because

$$\begin{gathered} R_{i \to \gamma\gamma} = \frac{d\sigma/dt(\pi^- p \to i(2\gamma)n)}{d\sigma/dt(\pi^- p \to \eta(2\gamma)n)} = \\ = R_i \frac{BR(i \to 2\gamma)}{BR(\eta \to 2\gamma)} = 0.00053. \end{gathered} \tag{26}$$

If one accepts $\Gamma(i) = 76$ MeV, then $BR(i \to 2\gamma) = 0.00073$.

Using here the obtained values of the mixing parameters and our earlier calculated /13/ Regge ones of the hypercharge exchange reactions we can make predictions for the differential cross sections of the reaction $K^- p \to \eta(\eta', i)\Lambda$ which are presented in Figs.5-7.

In conclusion, the authors would like to express their gratitude to A.B.Kaidalov for stimulating the work, and also to A.Yu.Khodjamirian for the useful discussions.

Table 1. The Regge parameters for $\pi^- p \to \eta(\gamma\gamma) n$ and $\pi^- p \to \eta'(\gamma\gamma) n$ reactions

	$\pi^- p \to \eta(\gamma\gamma) n$	$\pi^- p \to \eta'(\gamma\gamma) n$
a_0	0.287 ± 0.006	-0.0497 ± 0.0018
a_1	-1.155 ± 0.02	$+0.2112 \pm 0.0027$
R_0^2	1.329 ± 0.4	1.771 ± 0.5
R_1^2	1.213 ± 0.03	1.652 ± 0.05

Table 2. The parameters of the model

	Version 1	Version 2	Version 3	Version 4
m_G	1.234 ± 0.12	1.238 ± 0.054	1.256 ± 0.052	1.269 ± 0.034
λ_N	0.618 ± 0.06	0.616 ± 0.029	0.607 ± 0.025	0.601 ± 0.016
λ_S	0.507 ± 0.07	0.505 ± 0.033	0.494 ± 0.029	0.487 ± 0.018
λ_G	0.506 ± 0.07	0.504 ± 0.037	0.491 ± 0.042	0.4796 ± 0.32
χ^2/n	0	0.07	0.06	0.16

To be continued

Table 2. The parameters of the model

	Version 1	Version 2	Version 3	Version 4
η				
x_η	0.7192 ± 0.21	0.7197 ± 0.10	0.7222 ± 0.11	0.7236 ± 0.078
y_η	- 0.6888 ± 0.23	-0.6883 ± 0.11	-0.6861 ± 0.11	-0.6852 ± 0.081
z_η	- 0.09175 ± 0.62	-09119 ± 0.3	-0.08747 ± 0.06	-0.08302 ± 0.18
η'				
$x_{\eta'}$	-0.5654 ± 0.18	-0.5679 ± 0.086	-0.5804 ± 0.075	-0.5879 ± 0.06
$y_{\eta'}$	-0.6631 ± 0.23	-0.6651 ± 0.11	-0.6752 ± 0.099	-0.6816 ± 0.77
$z_{\eta'}$	0.4905 ± 0.59	0.4850 ± 0.28	0.4553 ± 0.24	0.4358 ± 0.17
i (1440)				
x_i	-0.3988 ± 0.17	-0.3946 ± 0.0.85	-0.3718 ± 0.076	-0.3550 ± 0.05
y_i	-0.2969 ± 0.14	-0.2934 ± 0.069	-0.2745 ± 0.061	-0.2613 ± 0.40
z_i	-0.8676 ± 0.47	-0.8708 ± 0.22	-0.8868 ± 0.18	-0.8976 ± 0.12

Table 3. The comparison with the experiment and the predictions

	Exp. values	Version 1
R from eq. (12)	0.62 ± 0.11	0.62 ± 0.11
R_i from eq. (25)		0.307 ± 0.4
$\Gamma(A_2\to\eta'\pi)/\Gamma(A_2\to\eta\pi)$		0.027 ± 0.005
$\Gamma(\eta\to 2\gamma)/\Gamma(\pi^0\to 2\gamma)$	41.21 ± 7.37	37.88 ± 10
$\Gamma(\eta'\to 2\gamma)/\Gamma(\pi^0\to 2\gamma)$	669 ± 237	674 ± 366
$\Gamma(i\to 2\gamma)$ KeV		7.08 ± 6
$\Gamma(\rho\to\eta\gamma)/\Gamma(\omega\to\pi^0\gamma)$	0.062	0.063 ± 0.036
$\Gamma(\varphi\to\eta\gamma)/\Gamma(\omega\to\pi^0\gamma)$	0.059 ± 0.013	0.076 ± 0.05
$\Gamma(\eta'\to\rho\gamma)/\Gamma(\omega\to\pi^0\gamma)$	0.098 ± 0.04	0.087 ± 0.054
$\Gamma(\varphi\to\eta'\gamma)/\Gamma(\varphi\to\eta\gamma)$		0.0043±0.0004
$\Gamma(i\to\rho\gamma)/\Gamma(\omega\to\pi^0\gamma)$		1.185 ± 1
$\Gamma(J/\psi\to\eta'\gamma)/\Gamma(J/\psi\to\eta\gamma)$	4.19 ± 1	5.08± 1.1
$\Gamma(J/\psi\to i\gamma)/\Gamma(J/\psi\to\eta\gamma)$	4.88 ±2.42	8.4±3

To be continued

Table 3. The comparison with the experiment and the predictions

Version 2	Version 3	Version 4
0.62 ± 0.07*)	0.65 ± 0.076	0.66 ± 0.048*)
0.29 ± 0.2	0.27 ± 0.18	0.28 ± 0.13
0.028 + 0.003	0.028 + 0.0026	0.028 + 0.002
37.99 ± 1.7*)	38.56 ± 1.5*)	38.87 ± 1.0*)
679 ± 82*)	707 ± 72*)	723 ± 46*)
6.93 ± 3	6.13 ± 2.5	5.58 ± 1.8
0.063 ± 0.02	0.084 ± 0.0012*)	0.064 ± 0.0006
0.075 ± 0.025	0.075 ± 0.0073*)	0.075 ± 0.001*)
0.087 ± 0.026	0.091 ± 0.01*)	0.094 ± 0.0009*)
0.0044±0.002	0.0045± 0.002	0.0044 ± 0.001
1.13±0.48	1.05±0.4	1.085±0.3
5.11±0.6	5.3±0.4	5.42±0.32
8.4±3	7.41±2.5	6.73±1.7

*) Quantities participating in the fitting procedure

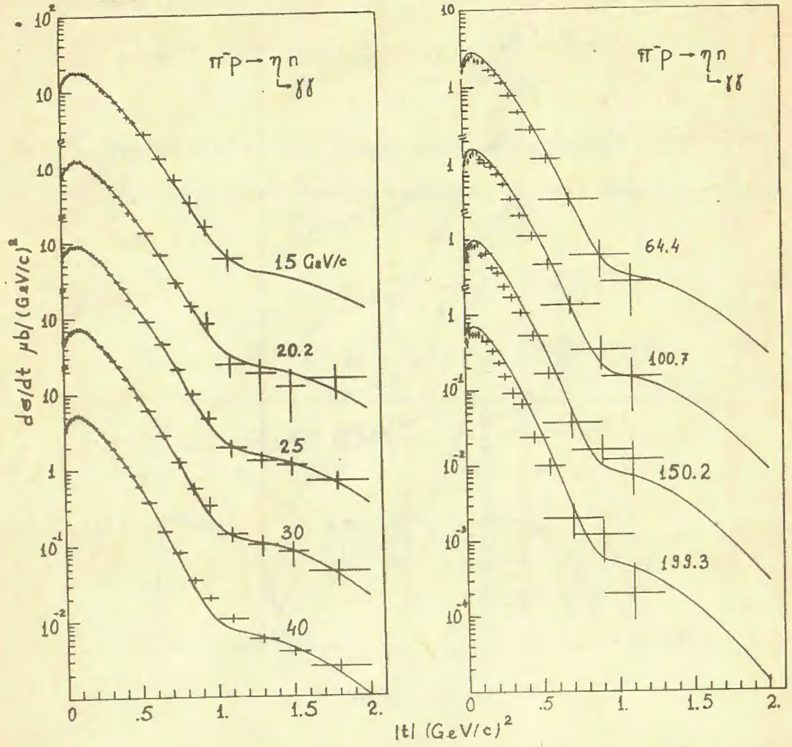

Fig.1. The differential cross sections for the $\pi^- p \to \eta n$, $\eta \to \gamma\gamma$ reaction.

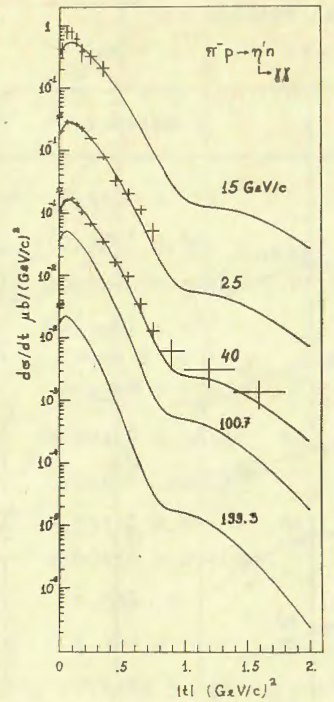

Fig.2. The differential cross sections for the $\pi^- p \to \underset{\hookrightarrow \gamma\gamma}{\eta'}\, n$ reaction.

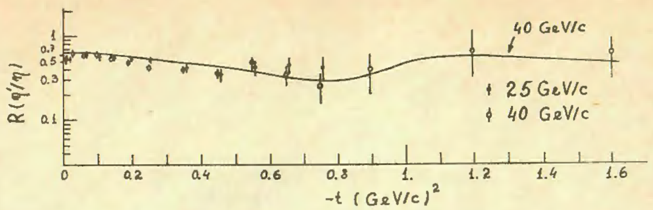

Fig.3. The ratio of the cross sections $d\sigma/dt(\pi^- p \to \eta\, \underset{\hookrightarrow \gamma\gamma}{n})$: $d\sigma/dt(\pi^- p \to \underset{\hookrightarrow \gamma\gamma}{\eta'} n)$ as a function of the transferred momentum.

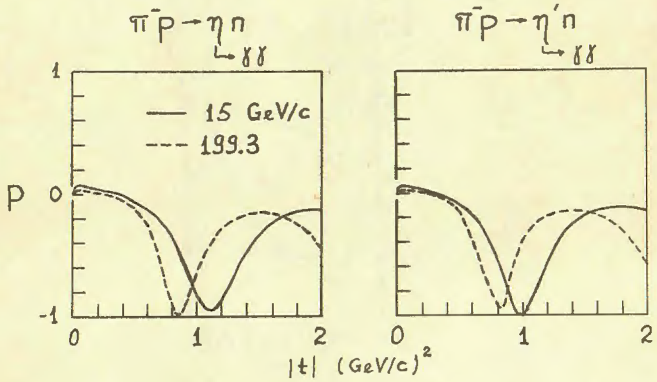

Fig.4. The polarizations in the $\pi^- p \to \underset{\hookrightarrow \gamma\gamma}{\eta\,(\eta')}\, n$ reactions.

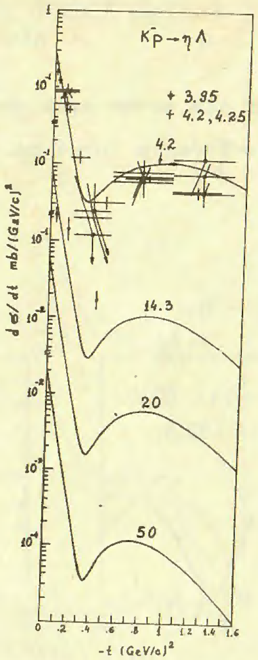

Fig.5. The differential cross sections for the $K^{-}p \to \eta\Lambda$ reaction.

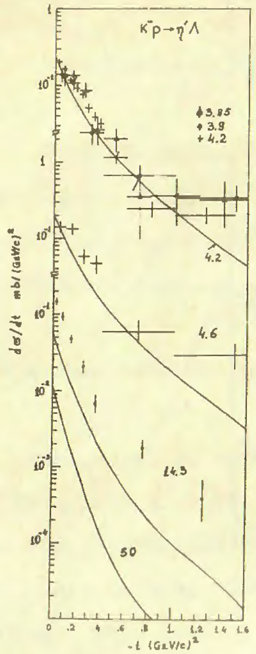

Fig.6. The differential cross sections for the $K^{-}p \to \eta'\Lambda$ reaction.

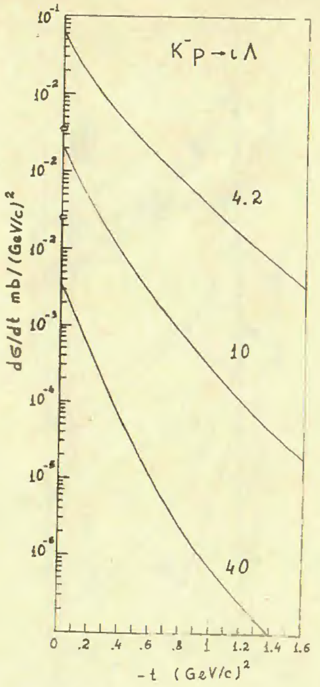

Fig.7. The differential cross sections for the $K^-p \to \iota\Lambda$ reaction.

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